Final Report - November 12, 1997

JPL D - 14879A

MICROEXPLORERS

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ABSTRACT

Inspired by the world of insects and animals, the well-proven natural 'explorers' on this planet, this study is a feasibility assessment of building efficient and cost-effective 'microexplorers' for future NASA missions. The continuously evolving science requirements for planetary in situ sensing, documented by NASA scientists, and examples of microrovers under development at the world's leading research institutions provide a realistic starting point for the study. Three broad volume envelopes (1 to 20 cc, size A; 10 to 200 cc, size B; and 100 to 2000 cc, size C) are considered for three somewhat overlapping categories of microexplorers. Rough order of magnitude estimates are then made of the mass, volume, and power requirements for on-board sensors, communication gear, computation, mobility, etc. Power considerations may restrict the breadth of sensing capabilities of the smallest size Category A explorers; however, a simple analysis suggests that all three size categories, utilizing alternative mobility modes, would offer an excellent range of in situ exploration opportunities and reasonable life-span and complement those of conventional large rovers. The study finally identifies technology development needs for realization of such microexplorers.

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This work was sponsored by the National Aeronautics and Space Administration

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EXECUTIVE SUMMARY

Inspired by the world of insects and animals, the well-proven natural ‘explorers’ on this planet, this study is a feasibility assessment of building efficient and cost-effective ‘microexplorers’ for future NASA missions. The continuously evolving science requirements for planetary in situ sensing, documented by NASA scientists, and examples of microrovers under development at the world’s leading research institutions provide a realistic starting point for the study. Three broad volume envelopes (1 to 20 cc, size A; 10 to 200 cc, size B; and 100 to 2000 cc, size C) are considered for three somewhat overlapping categories of microexplorers. Rough order of magnitude estimates are then made of the mass, volume, and power requirements for on-board sensors, communication gear, computation, mobility, etc. Power considerations may restrict the breadth of sensing capabilities of the smallest size Category A explorers; however, a simple analysis suggests that all three size categories, utilizing alternative mobility modes, would offer an excellent range of in situ exploration opportunities and reasonable life-span and complement those of conventional large rovers. The study finally identifies technology development needs for realization of such “bio-morphic explorers”.

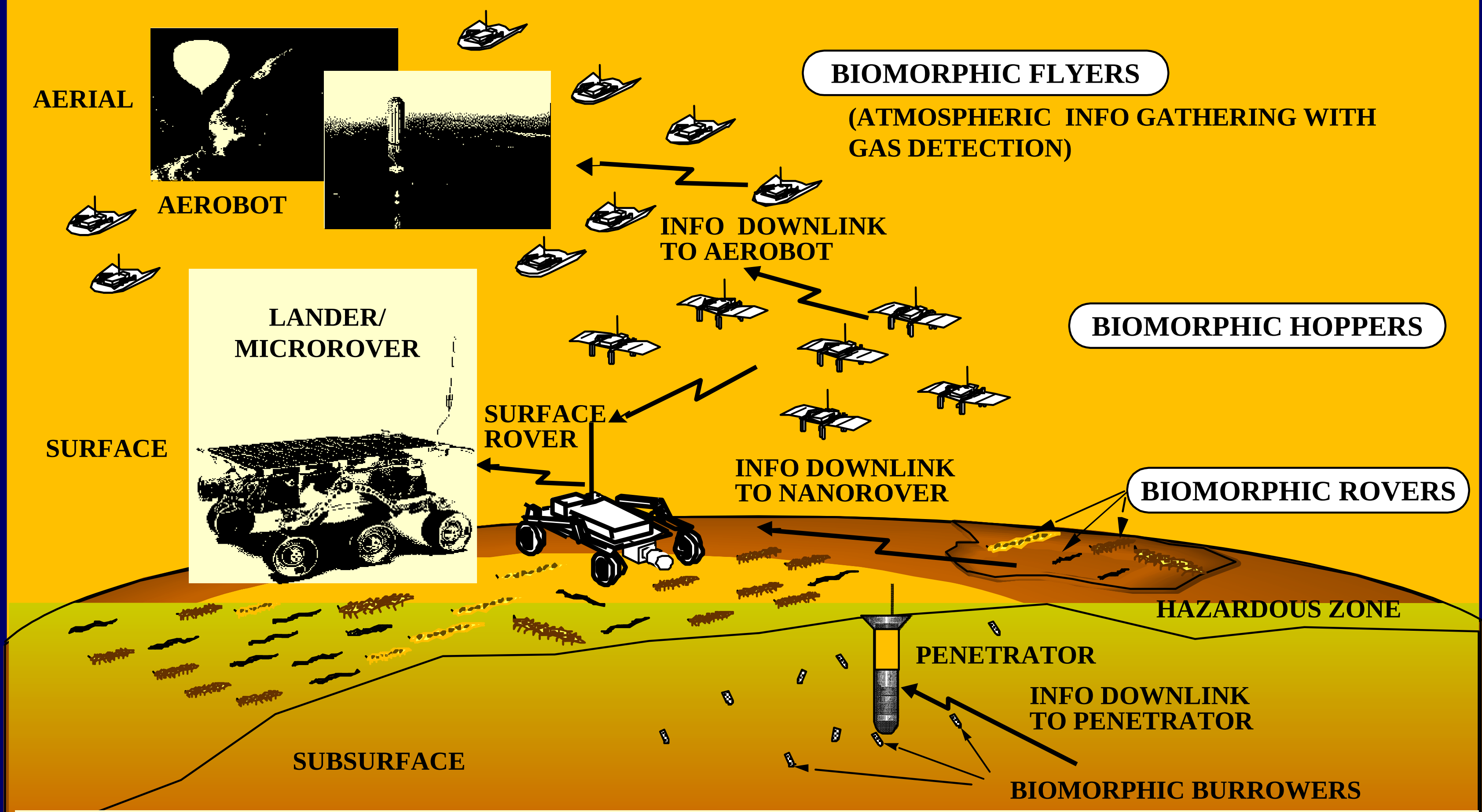
Realization of the vision of small expendable bio-morphic explorers requires at least four key components: (1) microsensors, (2) micropower, (3) advanced mobility, and (4) microcommunication devices. The development of three out of these four essential components (except the advanced mobility) is already driven by multibillion dollar commercial market forces. For example, sensors, such as imagers, are already being miniaturized to serve the voracious appetite of the digital imaging business in surveillance, security, science, and entertainment. Solid-state, high-power-density batteries are advancing at a rapid pace driven by the development in cellular phones, handheld computers, long-life watches, and other electronic gadgets. Low-power, limited-range, low-bandwidth communication, adequate for the explorers, has also been addressed aggressively in recent years to target the mass market of product ID tags and inventory control. However, the only component that has not received equivalent attention from the commercial market forces is advanced mobility. A recommendation of this study, therefore, is to invest in the research and development of innovative advanced mobility (embodied, for example, as foldable mobile units based on flexible actuators), adaptively controlled by emerging, bio-inspired control algorithms. Customization of the selected sensors to integrate them on specific microexplorer structures is another intense effort that is required. Concurrently, at the system level, strawman designs of multiple microexplorer options in each category are needed along with detailed engineering analysis to select the most suitable with emphasis on cost and science value. This can then lead to development of microexplorer prototypes and their demonstration for selected, NASA-relevant, planetary exploration applications.

Combining flexible actuators and bio-morphic controls would offer, for the first time, a new direction in autonomous exploration with adaptation to varying terrain conditions, enhanced spatial access, and ease of production due to reduced size and complexity. Autonomous exploration capability with these features would be quite beneficial in several scientific endeavours including search for evidence of life, in situ sensing to obtain physical/meteorological/chemical data on unexplored planet surfaces, and investigation of previously inaccessible locations, even on Earth such as lake Vostok or lake Nyos. Biomorphic explorers would also offer new capabilities for exploration, surveillance, and advanced warning systems.

INTRODUCTION

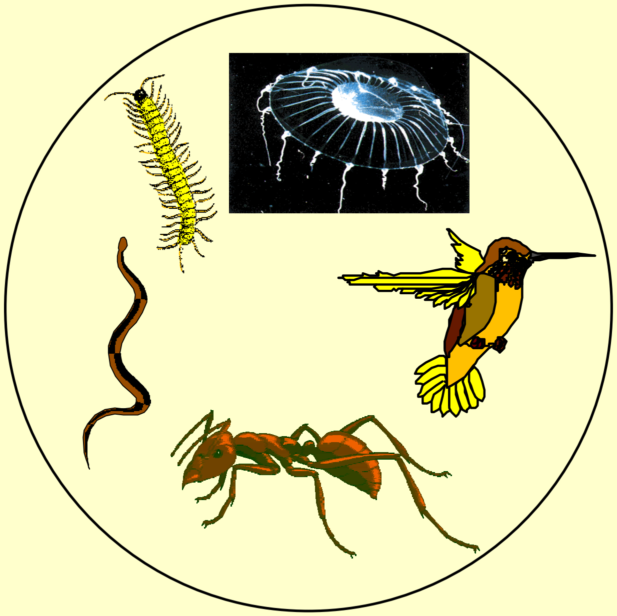
Sojourner's success on the surface of Mars has proven beyond doubt that a mobile platform on a planetary surface, equipped with sensors, can acquire a wealth of new science data. Ideal for taking numerous pictures, the rover by itself could, however, only "probe" chemical composition of a limited number of rocks during its first month on the surface. In-situ, autonomous exploration and science return from surfaces and subsurfaces would be substantially enhanced if a large number of small, inexpensive, and therefore dispensable, microexplorers equipped with dedicated microsensors could be spread over the surface by a lander or a larger rover. Mimicking biology, such microexplorers may possess animal-like mobility/adaptability. Their potential low-cost and small size may make them ideal for hazardous/difficult site exploration/inspection/testing. Their dedicated sensing functions and maneuverability would be invaluable in scouting missions and sample acquisition from hard to reach places. Such bio-morphic microexplorers would complement the capabilities of the larger and relatively expensive exploration vehicles (e.g. landers, rovers, and aerobots). Also, microexplorers may possess varied mobility modes: surface-roving, burrowing, hopping, hovering, or flying, to accomplish surface, subsurface, and atmospheric exploration. Preprogrammed for a specific function and spread over the exploration site, they could serve as intelligent, downlink–only beacons that autonomously look for objects of interest. In a hierarchical organization, these bio-morphic explorers would report their findings to a next higher level of exploration (say, a large conventional rover) in the vicinity. This would allow more wide-spread and affordable exploration at lower cost and risk by combining a fast running rover to cover long distances and deploying numerous microexplorers for in-situ sensing and local sample analysis/acquisition.

POTENTIAL COMPREHENSIVE EXPLORATION SCENARIO



HEIRARCHICAL ORGANIZATION OF LANDER, ROVER(S), PENETRATOR(S) AND A MULTITUDE OF INEXPENSIVE MICROEXPLORERS WOULD ALLOW COMPREHENSIVE EXPLORATION AT A LOWER COST

STUDY MOTIVATION AND OBJECTIVE



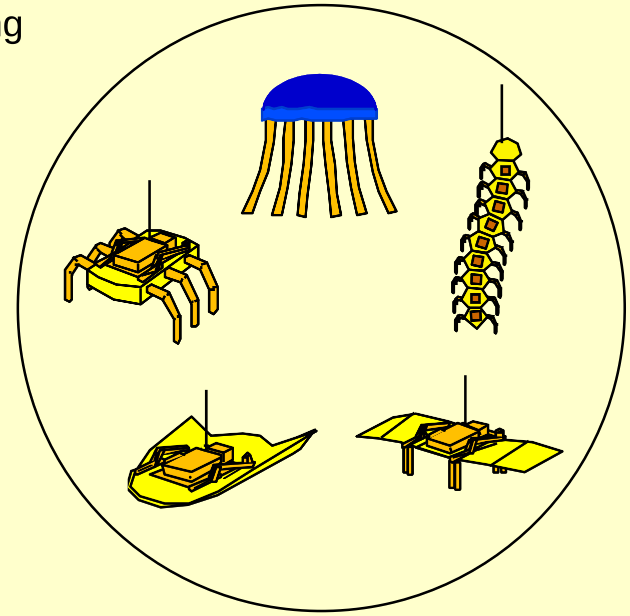
MOTIVATION:

Inspired by the numerous examples of successful "explorers" in biology, small, self-sufficient, "robotic" microexplorers may enhance planetary/ space exploration through:

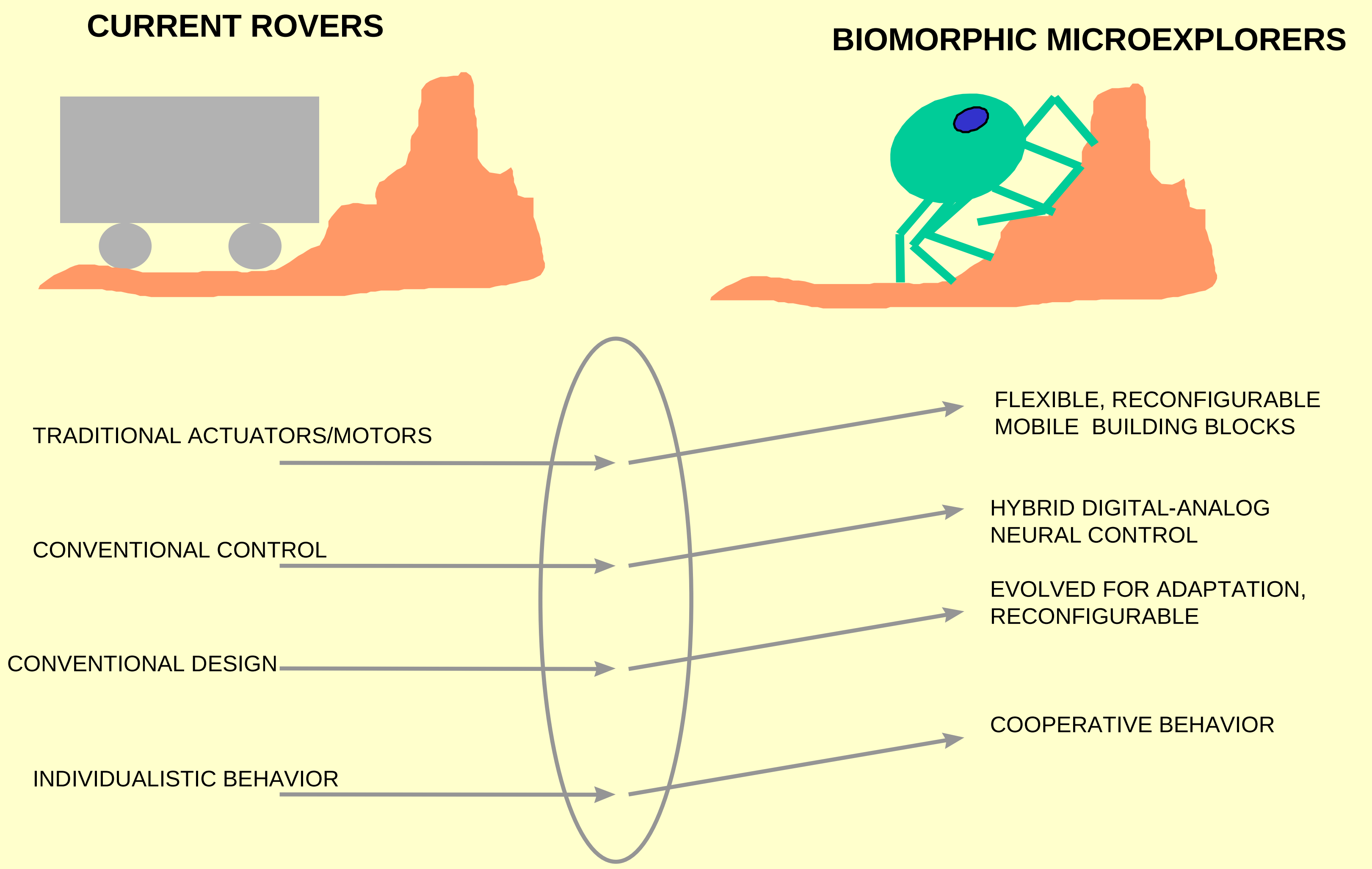
- Access to Hard-to-Reach and Hazardous Areas
- Better Spatial Coverage of Exploration Site
- Easy, Low-Burden, Add-on Science
- Dedicated Microsensing
- Low Recurring Cost

OBJECTIVE:

The specific objective of this study was to assess the feasibility of developing and using biomorphic microexplorers for meaningful, cost-effective scientific exploration in future space missions.



MOTIVATION: PARADIGM SHIFT FOR ENHANCED SCIENCE RETURN



PLANETARY IN SITU SENSING: SCIENCE REQUIREMENTS

A *REPRESENTATIVE* EXAMPLE: SEARCH FOR PAST OR PRESENT LIFE ON MARS..

- **To what extent did prebiotic chemical evolution proceed on Mars?**
- **If chemical evolution occurred, did it lead to synthesis of replicating molecules, i.e., life, which subsequently became extinct?**
- **If replicating systems arose on Mars, do they persist anywhere on Mars today?**

THE FIVE PHASES OF SYSTEMATIC EXPLORATION INCLUDE:

(1) GLOBAL RECONNAISSANCE for the identification of potentially fruitful sites for lander missions. Acquisition of global information on the distribution of water (either solid, liquid, chemically combined or physically adsorbed), global mapping of pertinent mineralogical/lithological regimes, thermal mapping, and high-resolution imaging of the martian surface

(2) LANDED MISSIONS providing ***in situ*** descriptions of sites identified during Phase 1. A geochemical and mineralogical characterization culminating in elemental, molecular and isotopic analysis of the biogenic elements in a variety of microenvironments and analysis of volatile species

(3) DEPLOYMENT OF EXOBIOLOGICALLY FOCUSED EXPERIMENTS. For chemical evolution, the goal would be a detailed characterization of any population of organic compounds on Mars. For the issue of extinct life, the task would be a search for biomarkers and for morphological evidence of formerly living organisms.

(4) ROBOTIC RETURN OF MARTIAN SAMPLES TO EARTH would greatly improve characterization of the organic inventory at specific martian locations and, furthermore, would be essential for verification of any in situ evidence for extinct or extant life obtained in Phase 3, leading to, finally,

(5) HUMAN MISSIONS...

CLEARLY, EXPLORATION PHASES 2, 3, AND 4 WILL BENEFIT FROM MICROEXPLORERS, WHEN USED IN CONCERT WITH LANDERS, ROVERS, PENETRATORS, ETC.

Ref: An exobiological Strategy for Mars exploration
http://cmex-www.arc.nasa.gov/Exo_Strat/exo_strat.html

SCIENCE FUNCTIONS

SCIENCE APPLICATIONS :

Combining flexible actuators and bio-morphic controls would offer for the first time a new direction in autonomous exploration with adaptation to varying terrain, enhanced spatial access, and ease of production due to reduced size and complexity. Significant benefits would be offered in several scientific applications including search for evidence of life, in-situ sensing to obtain physical/meteorological/chemical data on unexplored planet surfaces, and investigation of previously inaccessible locations, even on Earth such as lake Vostok or lake Nyos.

SEARCH FOR EVIDENCE OF LIFE :

The search for evidence of life outside of our terrestrial abode piques the public curiosity and is, therefore, a high-priority goal of NASA's future missions. The planet Mars and the Jovian satellite Europa are two prominent targets for search for evidence of life. Life sensing could include sensing for prebiotic materials such as amino acids, sensing for water, or identifying carbonates as evidence of extinct/extant life. Small expendable bio-morphic explorers would be particularly useful in the Phase 2 exploration, as identified in the exobiological strategy for Mars exploration (page 10), to obtain in-situ description of sites identified during Phase 1. Microspectrometers as small as 3 cm x 3 cm x 0.5 cm are commercially available that could be included in the payload. Sulfur dioxide sensors, to look for sulfur-chemistry -based life; carbon dioxide sensors for looking for carbonates; water sensors; and ultraminiature microscopes and microcameras are other potential microinstrument candidates for the search for evidence of life. Exploration for life may include a lander/rover (mothership) and multiple small explorers working in concert. "Multiple" here means not just a few but potentially 100's or 1000's of the explorers peppering the exploration site for an exhaustive survey. Constructed of foldable building blocks occupying low mass and volume, a large number of explorers could be stacked/stored on a long-range mother rover. For instance, in exploring ejecta from a crater, the mother rover could focus on traversing large distances (say ~ 10 Km, to cover the entire crater) and the bio-morphic explorers could be spread out to do localized sample survey/acquisition at every 100 m interval.

DISTRIBUTED SENSING:

Innovative state-of-the-art sensors for temperature, individual gases, elements, specific amino acid assay, radiation, etc., packaged in small volumes are ideal for the bio-morphic explorers. Any environmental measurement, in fact, might be more accurate using microexplorers with their minimal disruption of the environment, due to their small size, mass, and low thermal inertia. In particular, distributed temperature sensing as a function of depth is quite important for obtaining geophysical information, and it is a suitable task for earthworm-like burrowers. Typically state-of-the-art temperature sensors are quite small (e.g., ~ 500 micron x 250 micron) with small sense electronics. Distributed temperature sensing could, therefore, be the first objective to be achieved using bio-morphic explorers.

PLANETARY IN-SITU SENSING: SCIENCE REQUIREMENTS

SURFACE OBSERVATIONS AND IN-SITU MEASUREMENTS FOR DETECTION OF LIFE

To probe:	Use:	To obtain:
Texture of surface rocks	Visible camera	Sub-mm spatial resolution
Elemental abundance on the surface	Gamma ray spectroscopy	0.1 % by weight sensitivity
Near-surface water abundance	Pulsed-neutron gamma-ray spectroscopy	Hydrogen within half a meter of the detector
Surface mineralogy and local mapping	IR spectrometry followed by X-ray diffraction/fluorescence	Mineralogy with ~ 1 cm spatial resolution
Distribution of surface oxidant	Oxidant-specific chemical sensors	Distribution in all three dimensions, particularly vertical
Chemical character of microenvironment	PH, Eh (oxidizing potential) sensors	Understanding of conditions for survival of putative extinct or extant life forms
Presence of organic carbon	Carbon-sensitive detector	Dating of events/origins, exobiology
Elemental/isotopic analysis of bulk organic material	Combustion, gas purification and mass spectrometry	Exobiology
Molecular identity of organic carbon	Chromatographic or Other techniques of separation	Detection of lipids, amino acids, and carbohydrates
Biomarkers at the poles	Combination of gas and Chemical/reaction sensor	Detection of entrained gases (CH4, H2, H2S, etc.)
Gaseous biomarkers	Wind direction and speed sensors	Locating point sources of gas emanation

Ref: Planetary Surface Instrument Workshop
http://cass.jsc.nasa.gov./pub/publications/psiw/l

SENSING FUNCTIONS APPROPRIATE FOR MICROEXPLORERS

SURFACE OBSERVATIONS AND IN SITU *MEASUREMENTS:*

- **Clearly, chemical in situ sensing dominates the science requirements aimed at detection of present and/or past life on a planet.**
- **The complexity, size, and mass of the conventional sensor subsystems vary significantly.**
- **Inspired by the extremely sensitive "olfactory system" from biology, the rapidly emerging chemical sensors based on the 'electronic-nose' concept would be ideal for microexplorers.**
- **In addition, several physical sensors are intrinsically small and therefore prime candidates for smaller explorers:**

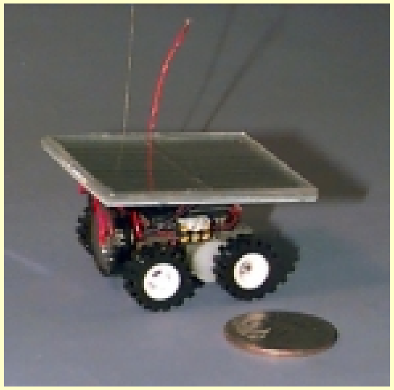
To probe:	**Use:**	**To obtain:**
Temperature: ambient, surface, sub-surface	thermistors	Temperature depth profile with a mm resolution
Wind direction, speed	Strain gauge sensors	High sensitivity, time dependence
Gases, elements	Chemical sensors	Local variations
Radiation	Radiation monitor	Specificity, dose rate, cumulative dose, energy
Particles/dust	microbalance	Total mass, flux
Seismic activity	Micro-machined seismometer	Local occurrences
Surface hardness	Strain gauge probe	With ~ mm spatial resolution

EXPERIMENTAL "MICROROVER" EXAMPLES

- **Microrobots and microrovers have attracted a great deal of research attention in recent years.**
- **Various combinations of wheeled and legged mobility mechanisms have been combined with a variety of sensors, power sources, navigation/control algorithms, and communication devices.**
- **Although an extensive survey of the state-of-the-art is beyond the scope of this study, a representative cross-section, illustrating feasibility of the microexploration concept, is presented in the following.**

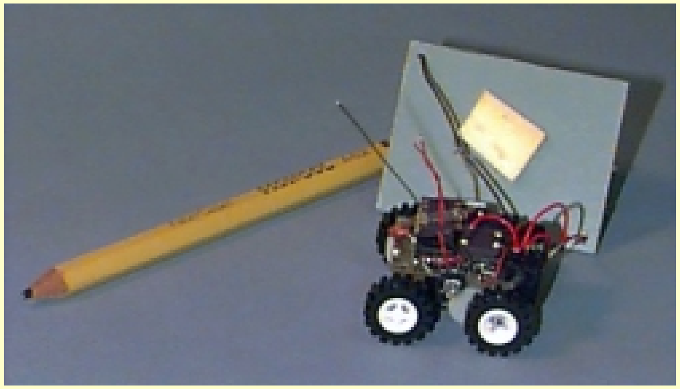
EXPERIMENTAL "MICROROVER" EXAMPLES

Solette



Scale comparison with a penny

Solette: Internal Structure



Top open, scale comparison with a pencil

Solette weighs ~ 30 grams, is completely autonomous, and is solar powered. There is a 9600 baud radio transceiver for communication with the base station. The energy collected from the solar panel is stored in a one farad capacitor to power the robot. *On robots of this scale, wheels turn out to be the limiting mobility factor, since most obstacles are larger than the robot.*

The answer to the wheel problem? Hop! The goal for the next robot, currently under development, is to be a 15 gram hopper (Hopette) with a camera, in addition to all the other components from Solette.

Rodney A. Brooks (brooks@ai.mit.edu)

Professor of Computer Science and Engineering (EECS Dept), and Associate Director of the Artificial Intelligence Laboratory at the Massachusetts Institute of Technology.

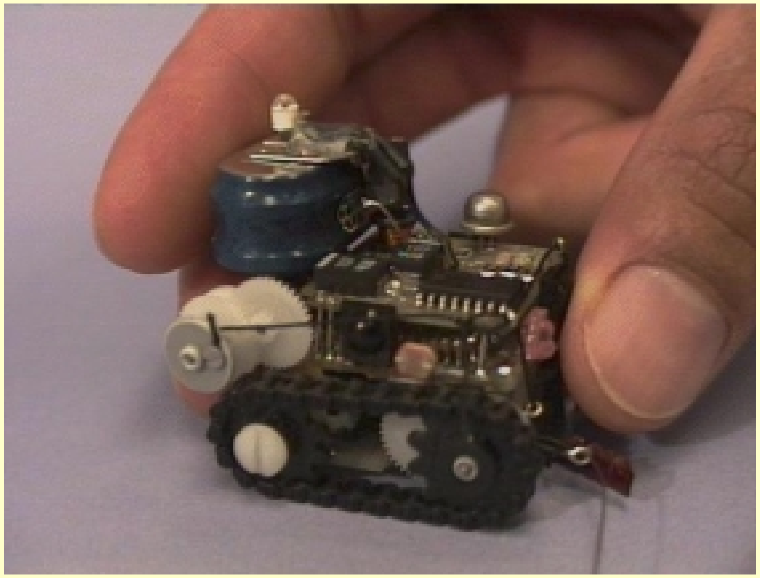
EXPERIMENTAL "MICROROVER" EXAMPLES

The Ants: A Community of Microrobots

The Ants are a community of cubic-inch microrobots at the MIT Artificial Intelligence Lab. There are two main goals for this project. The first is to push the limits of microrobotics by integrating many sensors and actuators into a small package. The second is to form a structured robotic community from the interactions of many simple individuals. The inspiration behind this idea comes from nature -- the ant colony.

In order to accomplish these goals, the robots have been equipped with sensors and actuators designed with their natural counterparts in mind. Each robot has 17 sensors including; four light sensors, four IR (infrared) receivers, bump sensors, food sensors, and a tilt sensor. They communicate with each other using two IR emitters, one mounted on the front of the robot and one mounted on the top.

There are several levels of social behavior before reaching the goal of the ant colony. Right now, the robots can play Follow the Leader, Tag and Manhunt. Manhunt is similar to tag except there are two teams. The final game before the full-fledged Ant Farm is Capture the Flag.



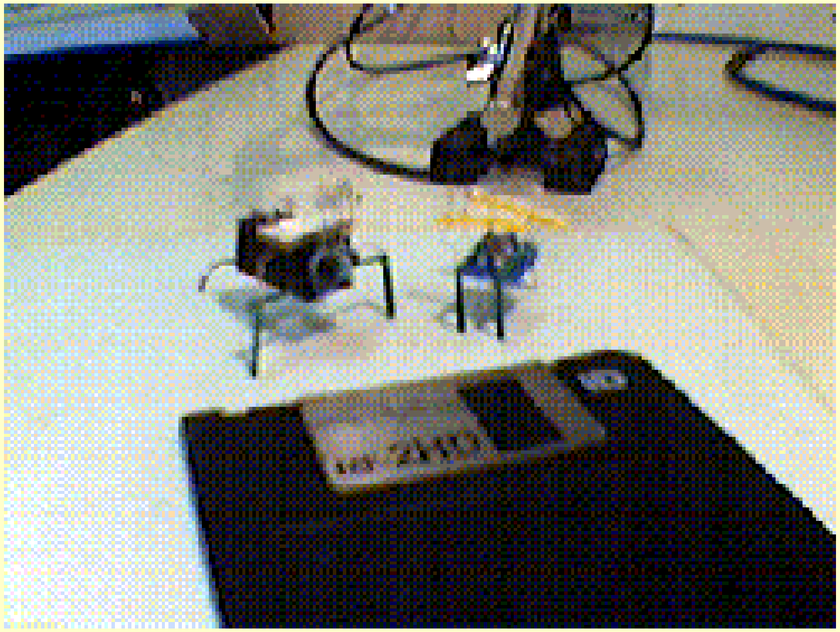
Rodney A. Brooks (brooks@ai.mit.edu)

Professor of Computer Science and Engineering (EECS Dept), and Associate Director of the Artificial Intelligence Laboratory at the Massachusetts Institute of Technology.

EXPERIMENTAL "MICROROVER" EXAMPLES

PLIF : Piezo Light Intelligent Flea

PLIF are walking microrobots with three legs; two legs are moved by means of piezo ceramics bimorph actuators, while the third is only passive. These robots are very small (2 cm X 2 cm) and very light (a few grams) but, at the same time, relatively fast (20 cm/s). Applications of these kinds of microrobots would be found in inspection of small environments, micro-surgery, study of cooperating systems, etc.. Three different versions of these robots have been built and an automatic-learning, soft-computing algorithm has been implemented to allow the microrobots to act as prey or a predator. The main peculiarity of the PLIF robots is that their single steps are very short in length (a few microns) but the legs move at high frequency (800Hz) so that a considerable speed can be reached.



Fabio De Ambroggi et al, Proc. Int. Conf. on Robotics and Automation (ICRA, 1997)

Ref: http://sun158.dees.unict.it/~giovanni/PLIF.html

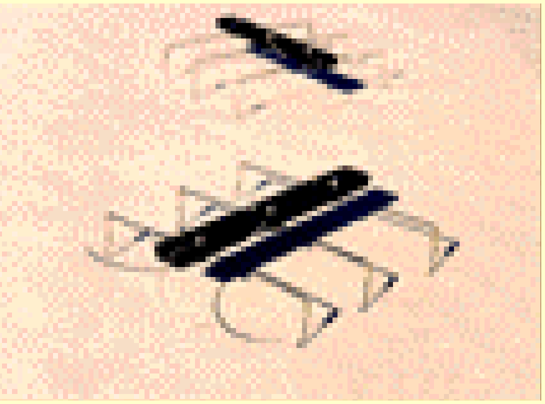
EXPERIMENTAL "MICROROVER" EXAMPLES

The Computer Science Department's Robotics Laboratory at Indiana University (Bloomington) has designed, built, and tested "Stiquito," a six-legged robot that you customize by adding sensors, controllers, power sources, etc. The robot provides an inexpensive platform to study computational sensors, subsumption architectures, neural gait control, emergent cooperative behavior, and machine vision. It is currently being used for research at IU, and, at a ratio of one robot per student, in "VLSI for Robotics" and "Machine Learning" classes.

Stiquito is small (3 cm H x 7 cm W x 6 cm L) and simple (32 parts) because its legs are propelled by nitinol actuator wires. Each leg has one degree of freedom. The robot walks up to 10 centimeters per minute and can carry a 9-volt cell, a MOSIS "tiny chip" and power transistors to drive the nitinol actuator wires. Alternatively, power and control can be supplied through a tether.

A single robot costs between $10 and $30. The pro-rated cost of materials to construct robots in volume (200 or more) is less than $3 each. The design can be replicated to build complex arthropods or colonies containing hundreds of insectoid robots.

Stiquito: A Small Nitinol-Propelled Hexapod Robot



Ref: http://www..cs.indiana.edu/robotics/robotics.html

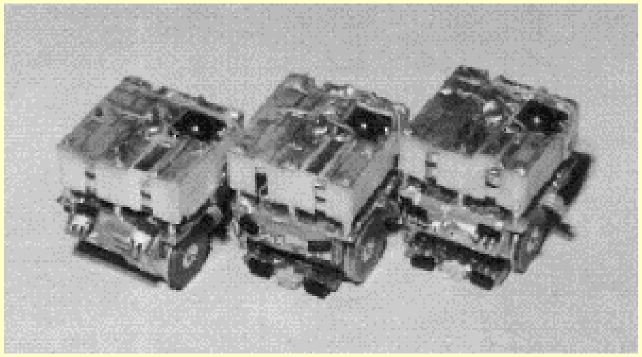
EXPERIMENTAL "MICROROVER" EXAMPLES

Prof. Toshio Fukuda from the Laboratory of Micro System Control of Nagoya University is another leading figure in microrover research. For example, his Programmable Micro Autonomous Robotic System (P-MARS) is a fully autonomous micro robotic system with a

- **CPU (16 bit),**
- **on-board memory (62 K ROM and 2 K RAM),**
- **actuators (miniaturized motors),**
- **sensors (a bank of custom-photosensors),**
- **communication devices (infra-red, line-of-sight),**
- **and small batteries,**

all built into a volume of less than a cubic inch.

Programmable Micro Autonomous Robotic Systems



P-MARS

In fact, his comprehensive work is also focussing on:

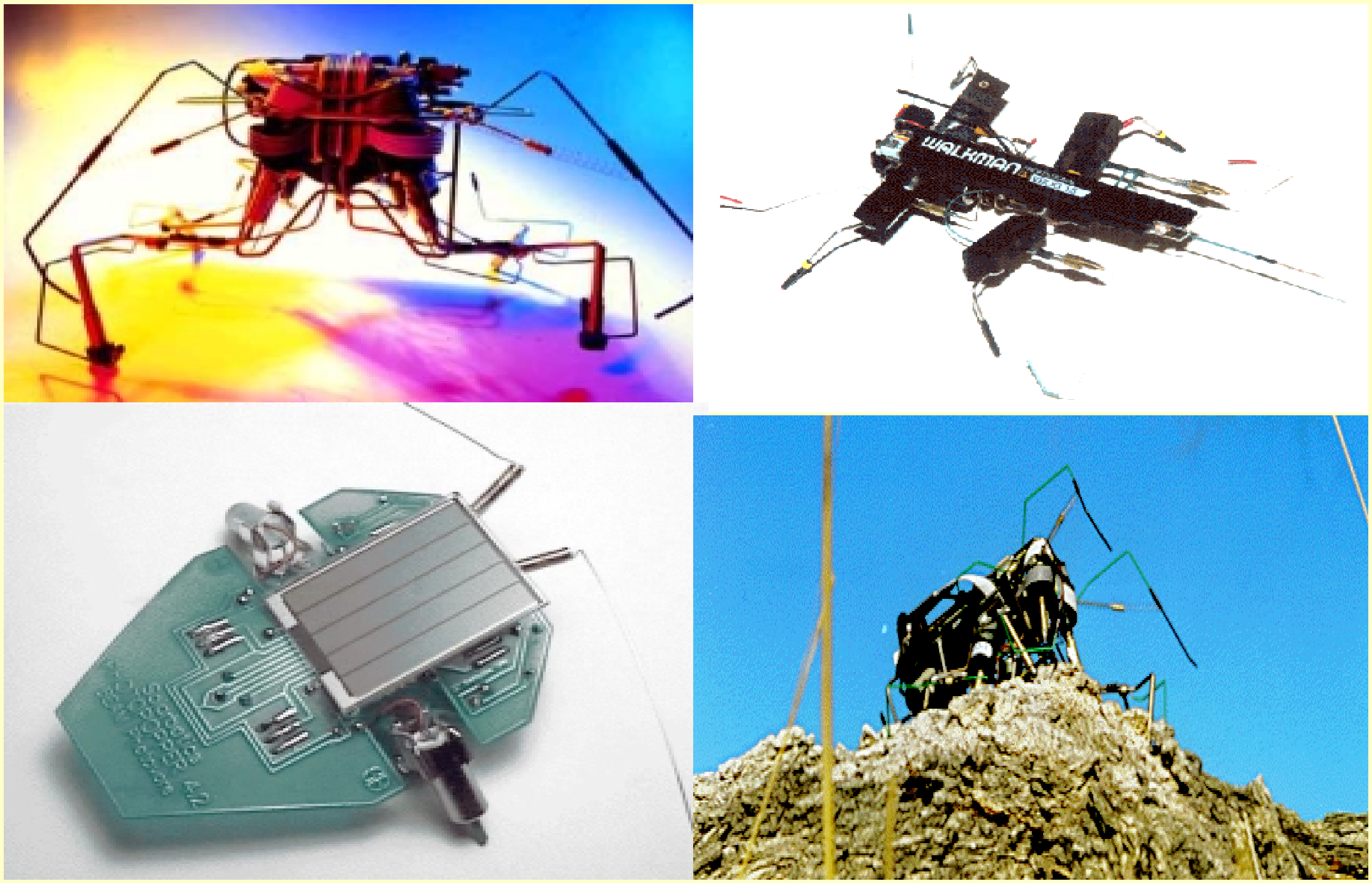
- **Algorithms for cooperative distributed sensing by Multiple Mobile Robots, sharing information from the environment to coordinate motion and dynamic structure reconfiguration**
- **Microsensors for force measurement, based on laser Raman spectrophotometer and miniaturized semiconductor strain gauges**
- **Micro manipulators and end effectors based on micro physics**

Fukuda et al: Rob. Automation, 2, 618, (1993); Special Issue on Evolutional Robots, Robotics and Autonomous Systems, Vol 16, #2-4 (1995)

Ref: http://www.mein.nagoya-u.ac.jp/

EXPERIMENTAL "MICROROVER" EXAMPLES

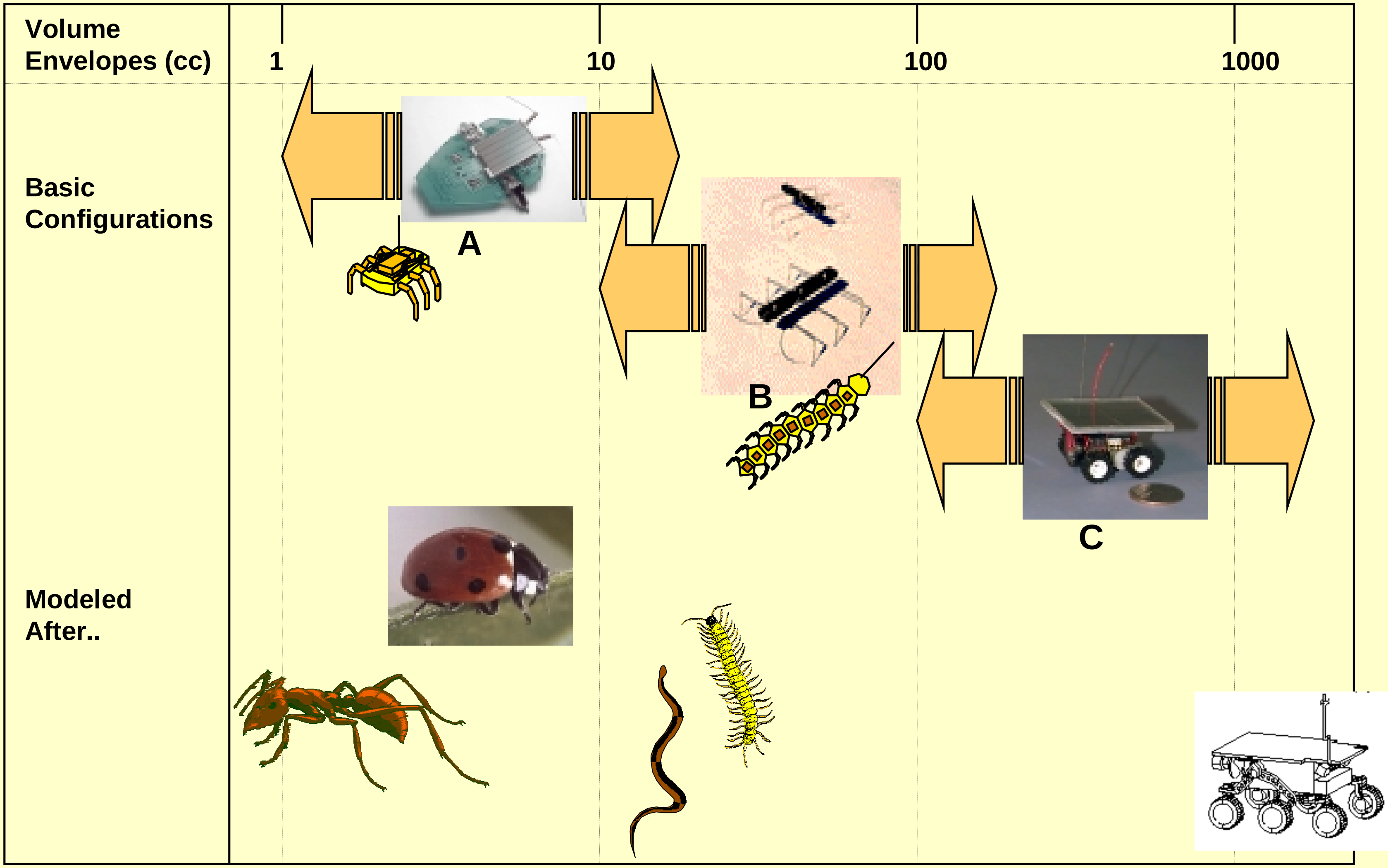
AND MANY MORE "[ARTIFICIAL INSECTS]" ..



Ref: http://www.solarbotics.com, M. W. Tilden, LANL

MICROEXPLORERS: BASIC CANDIDATE CONFIGURATIONS

Restricting this study only to explorers capable of traversing terrain...



MICROEXPLORERS: BASIC CANDIDATE CONFIGURATIONS

Restricting this study only to explorers capable of traversing terrain...

Volume Envelopes (cc)	1 A 10	B 100	C 1000
Basic Configurations			
Description:	• ~1 to 20 cc volume envelope • ~0.2 to 5 g mass • Direct-driven, legged or muscular- limb-based mobility mechanism • 6 or 8 legs, like an ant, lady bug or a spider; fixed structure.	• ~10 to 200 cc volume envelope • ~2 to 50 g mass • Direct-driven, legged or muscular-limb-based mobility mechanism; multiple legs/limbs, segmented, modular body, like a snake or centipede. Could be concatenated version of Category A	• ~100 to 2000 cc volume envelope • ~20 to 500 g mass • Direct-driven, legged (or conventional wheeled) mobility mechanism • This size is closer to a small animal than a large insect.
Sensors:	• Single “needle” sensor and single antenna for telecom	• Multiple needle sensors and antennae for sensing the local environment, or may include micro-imagers	• Sensors may include miniaturized camera, optical micro-machined spectro-meters, dedicated chemical sensors

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MICROEXPLORERS: FUNCTIONAL MODULES

- **Realization of the vision of small expendable “terrain-traversing” explorers would require four key components:**
    - **microsensors,**
    - **power,**
    - **advanced mobility, and**
    - **communication**
- **The development of three out of these four essential components (except the advanced mobility) is already driven by multi-billion dollar commercial market forces. For example:**
    - **Each of the sensors exists for a single, simple measurement such as temperature (a thermistor), chemicals (the electronic-nose), surface hardness (a strain gauge), and wind (also a strain gauge) is typically quite small and could be integrated as a part of an “antenna” or “stinger” in a size Category A or B explorer (page 28).**
    - **Sensors such as imagers are already being miniaturized to serve the voracious appetite of digital imaging in surveillance, security, science, and entertainment, and may be appropriate for a size Category C explorer. Optical micro-machined spectrometers, dedicated chemical sensors, etc are other potential candidates for a Category C payload (page 33).**
    - **Solid-state high-power-density batteries are advancing at a rapid pace driven by the development in cellular phones, handheld computers, long-life watches, and other electronic gadgets (page 24).**
    - **Low-power, limited-range, low-bandwidth communication, adequate for the explorers, has also been addressed rather aggressively in recent years to target the mass market of product ID tags and inventory control (page 34).**
- **Depending on the sensor function desired and expected ambient conditions, a microexplorer could range from just a few cc in volume up to several hundred cc in volume.**
- **Based on the current technologies, rough order-of-magnitudes of power required, and mass/ volume/size for a sensor, communication, on-board computing, and mobility for the size Category A, B, and C explorers are estimated in the following. Clearly, an extensive system study and analysis would be required for design of an operational prototype.**

MICROEXPLORERS: FUNCTIONAL MODULES
POWER: 'STATE-OF-THE-ART' BATTERIES

The state of the art in space-relevant batteries* available today:

- **Energy Density of Primary Batteries**

• lithium-thyniol chloride	~300 W-h/kg	JPL

- **Energy Density Secondary Batteries**

• nickel-cadmium (NiCd)	~36 W-hr/kg	
• nickel-hydrogen (NiH2)	~49 W-hr/kg	SSTI
• silver zinc (AgZn)	~90 W-hr/kg	
• sodium sulfur (NaS)	~200 W-hr/kg	Wright Lab
• lithium polymer	~200 W-hr/kg	3M
• Li/CoO2	~200-300 W-hr/kg	(Experimental)

- **For the purpose of this study, a scalable, secondary battery with 100W-hr/kg is a conservative estimate based on existing functional batteries**

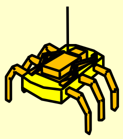
* http://www.hq.nasa.gov/office/oss/osstech/tech_db/112.htm

MICROEXPLORERS: FUNCTIONAL MODULES

POWER / VOLUME / MASS ALLOCATIONS

The next three pages list rough-order-of-magnitude allocations for the four main components of a representative microexplorer from each size category

Size Category A: Selected size: ~10 cc volume envelope, ~2.5 g mass



- **Direct-driven, legged/muscular-limb mobility mechanism based on advanced actuators e.g., shape memory alloy wires, PZT/PLZT actuators, and polymeric combinations**
- **Thin "antenna" (facing up) and/or sharp "stinger" (facing down)**

	Sensor	Communication	Computation	Mobility & Infrastructure* Incl. batteries
Function Performed	Temperature (Thermistor), Chemicals (electronic-nose), Surface Hardness (Strain Gauge), Wind (Strain Gauge) (Only one of the above)	Periodic Beacon And/Or "Eureka" Signal When Goal Accomplished Range ~15 to 50 m	Sensor Control, Signal/Data Conditioning, Motion/Articulation, Communication	Locomotion (~1 cm/sec), Limb Articulation, Adaptive Shape Reconfiguration
Power	~0.1 mW	~20 mW	~20 mW	~40 mW
Mass	~0.2 g	~0.4 g	~0.4 g	~1.5 g
Volume/Size	~0.2 cc	~0.2 cc	~0.2 cc	~9 cc

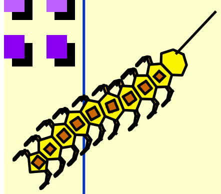
- **Even with only a single sensor, selecting a power source for such a small explorer body would be a challenge. For these allocations, using a '1 g' thin film battery with a 100 mW-hr/g energy density would give a reasonable 'mobility' life time of approximately over an hour for the explorer, with continuous sensing and infrequent communication.**

∗ **Infrastructure here includes basic structure, battery, electronics for power distribution and management, interconnects, and temperature control.**

MICROEXPLORERS: FUNCTIONAL MODULES

POWER / VOLUME / MASS ALLOCATIONS

Size Category B:



Selected size: ~100 cc volume envelope, ~25 g mass

- **Direct-driven, legged/muscular-limb mobility mechanism based on advanced actuators e.g., shape memory alloy wires, PZT/PLZT actuators, and polymeric combinations**
- **Multiple antennae and needle sensors for sensing the local environment**

	Sensor	Communication	Computing	Mobility & Infrastructure * Incl. batteries
Function Performed	Temperature (Thermistor), Chemicals (e-nose), Surface Hardness (Strain Gauge), Wind (Strain Gauge) (One or more of the above)	Periodic Beacon And/Or "Eureka" Signal When Goal Accomplished Range ~15 To 100 m	Sensor Control, Signal/Data Conditioning, Motion/Articulation, Communication	Locomotion (~1 cm/sec), Limb Articulation, Adaptive Shape Reconfiguration
Power	~0.4 mW	~50 mW	~50 mW	~400 mW
Mass	~0.4 g	~0.8 g	~0.8 g	~23 g
Volume/Size	~0.5 cc	~0.5 cc	~0.5 cc	~98 cc

- **With an estimate of a peak power consumption of ~ 500 mW, a '10 g' battery on-board (with a 100 mW-hr/g energy density) will offer ~ 2 hours of operation**

∗ **Infrastructure here includes basic structure, battery, electronics for power distribution and management, interconnects, and temperature control.**

MICROEXPLORERS: FUNCTIONAL MODULES

POWER / VOLUME / MASS ALLOCATIONS

Size Category C:

Selected size: ~1000 cc volume envelope, ~250 g mass

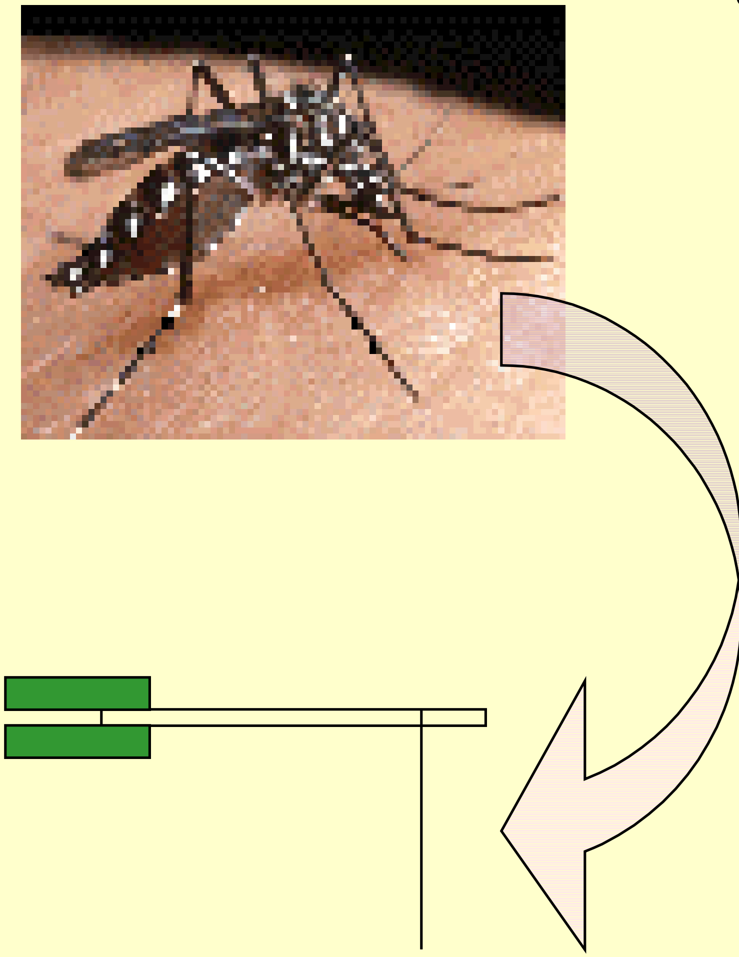
- **Direct-driven, legged (or conventional wheeled) mobility mechanism**
- **In addition to point sensors, class C explorers may include miniaturized cameras, optical micro-machined spectrometers, dedicated chemical sensors, etc.**

	Sensor	Communication	Computing	Mobility & Infrastructure * Incl. batteries
Function Performed	Temperature (Thermistor), Chemicals (e-nose), Surface Hardness (Strain Gauge), Wind (Strain Gauge) Microimager (APS Camera) Micro-spectrophotometer	Periodic Beacon And/Or “Eureka” Signal When Goal Accomplished Range ~100 m To 10 Km	Sensor Control, Signal/Data Conditioning, Motion/Articulation, Communication	Locomotion (~1 cm/sec), Limb Articulation, Adaptive Shape Reconfiguration
Power	~500 mW	~500 mW	~1000 mW	~2 W
Mass	~5 g	~20 g	~20 g	~200 g
Volume/Size	~10 cc	~5 cc	~5 cc	~980 cc

- **These allocations suggest a peak power consumption of ~ 4 W. Therefore, a ‘100 g’ battery on-board (with a 100 W-hr/kg energy density) will offer ~ 2.5 hours of continuous operation.**

* **Infrastructure here includes basic structure, battery, electronics for power distribution and management, interconnects, and temperature control.**

MICROEXPLORERS: FUNCTIONAL MODULES
CANDIDATE SENSOR STRUCTURE: “NEEDLE” SENSOR



Point Sensors for Size Category A and B:

A flexible but sharp, syringe-like stinger of a mosquito is an excellent example from biology of a piercing probe.

Extremely light-weight, it is still strong enough to break through the skin.

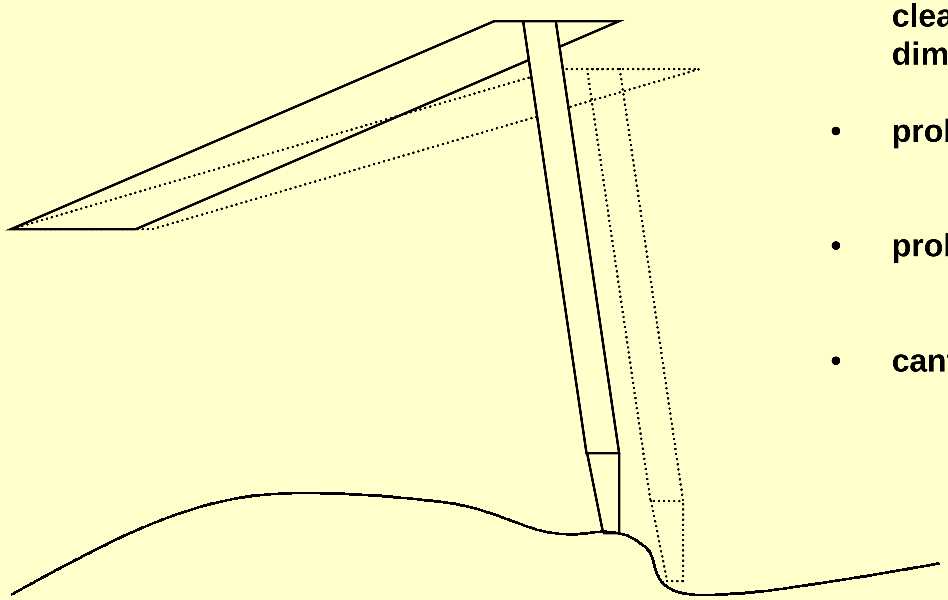
Inspired by the stinger, a single point, “needle” sensor holding a micro-thermistor (page 30) is ideal for temperature measurement of the air or ground.

The ceramic, flexible, cantilevered support arm, equipped with a strain gauge (page 31) and other printed electronic circuitry would also keep track of contact with the (ground/soil) surface, surface hardness, and possibly surface texture.

A miniaturized electronic-nose (page 32, solid-state tailored chemical sensor for one or more specific chemicals) mounted on the needle is an obvious extension of the “needle” concept to increase the effectiveness of such a simple sensor probe for in-situ sensing.

MICROEXPLORERS: FUNCTIONAL MODULES
CANDIDATE SENSOR STRUCTURE: "NEEDLE" SENSOR

A Schematic diagram of a 'needle' probe mounted at the tip of a cantilever



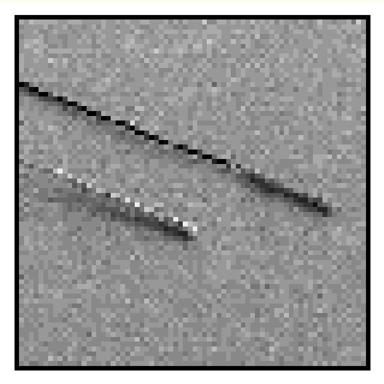
The probe tip would touch the ground to read:
- **the surface temperature,**
- **the physical profile,**
- **surface hardness, softness**
- **presence/absence of a chemical**

Although the sensor structure suggested here is clearly scalable over a wide range of dimensions, candidate dimensions could be:

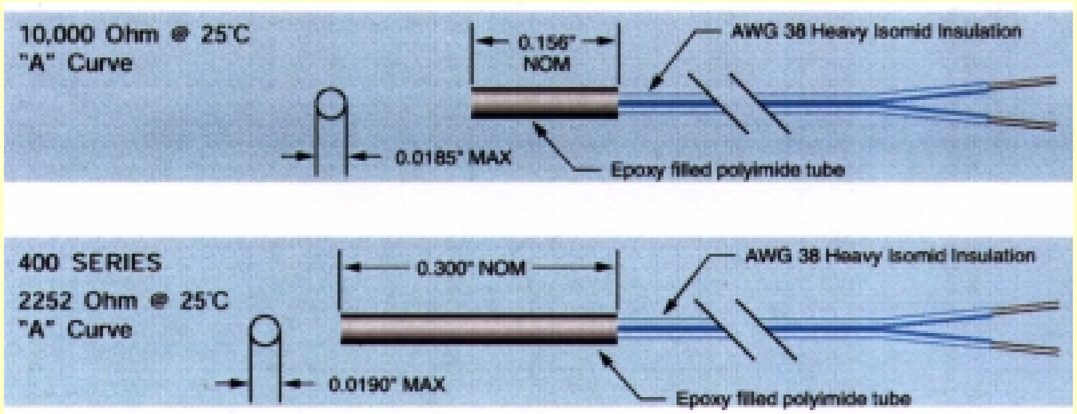
- **probe width (needle diameter): ~ 500 μ m**
  - **sufficient for housing the variety of point sensors discussed herein.**
- **probe length: ~ 3 to 5 mm**
  - **dictated by overall design considerations**
- **cantilever length: ~0.5 to 1.5 cm**
  - **appropriate for mounting strain gauge(s) as well as other active readout electronics.**

MICROEXPLORERS: FUNCTIONAL MODULES
DEDICATED SENSOR: THERMISTOR

The ‘needle’ sensor structure described on the previous charts is ideally suited for “holding” a micro-thermistor. A commercial product that could be virtually used “as is” is presented below. Of course, further customization will result in better fit with a selected geometry.



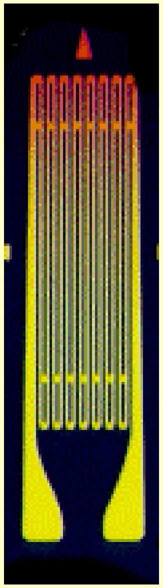
Alpha’s micro thermistors are specifically designed for applications where small size, fast response, and tight tolerances are crucial requirements. These are small enough to fit into a hypodermic needle and have a typical 250 millisecond time constant.



Ref: http://www.designinfo.com/scripts/search.exe/toc?VID=200&Comp=16

MICROEXPLORERS: FUNCTIONAL MODULES
DEDICATED SENSOR: STRAIN GAUGE

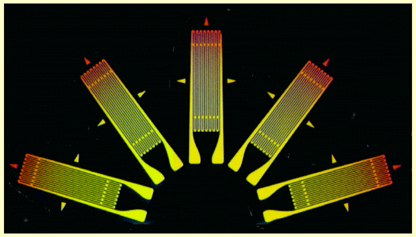
The needle sensor structure is also appropriate for mounting a custom-designed piezo-resistive strain gage element on it. In particular, a strain gage element could be mounted/deposited on the cantilevered arm holding the stinger, and would be capable of sensing the force experienced by the tip of the stinger.



For example, Texas Measurements, Inc; manufacturer of Strain Gages and Strain Instrumentation, offers:

- **Standard wire strain gauges (their "P" Series Strain Gages) which have a transparent plastic backing impregnated with a polyester resin. Gages are available in one, two, and three axis "stacked" configurations, and in lengths from 20 to 120 mm.**
- **Their "F" series gages are foil strain gages with an extremely thin epoxy backing. They are produced from specially controlled alloy foils with thicknesses from 0.003 to 0.007 mm. They are available in lengths as short as 0.02 mm, for use in measuring extremely high stress gradient concentrations, to 30 mm long. Over 20 different standard and specialized gage patterns are available for measuring normal stresses, residual stresses, shear strains, etc. One, two, and three axis gages are available, in both stacked and side-by-side gage patterns.**
- **Sensing Element: Cu-Ni Foil**
- **Operational Temperature Ranges:**

  Short-term or Special: -196 to +80 °C
  Normal: -20 to +80 °C
  Temperature compensation range: +10 to +80 °C

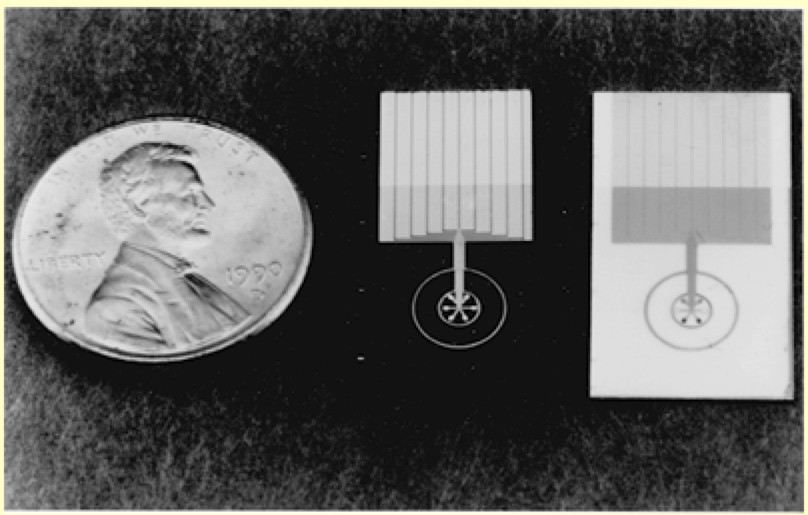


- **Strain Limit: 3%**
- **Fatigue Life: 1x10E5 at +/- 1500xE-6 strain, at 15Hz**
- **Clearly, such strain gages could be easily customized and adapted for selected microexplorer configurations.**

Ref: http://www2.cy-net.net/~lowery/straingage/

MICROEXPLORERS: FUNCTIONAL MODULES
DEDICATED SENSOR: CHEMICAL SENSOR

The needle sensor structure could also hold a chemically sensitive thin film as a micro-chemical sensor (with high specificity and reversibility). An electronic nose is a tailored 'conductor' in a wheatstone-bridge-like 'balance' circuit; it is easy to miniaturize. The following shows a few examples of Earth-based applications



APPLICATIONS

- Environmental pollution monitoring
- Industrial, process-control monitoring
- Medical, bedside monitoring

Ref: R.S. Glass, 1997

MICROEXPLORERS: FUNCTIONAL MODULES
DEDICATED SENSOR: MICROIMAGER

Micro-imagers based on Active Pixel Sensor (APS):

Camera size comparison with a penny

Ideal for Size Category C

- **World's smallest low-cost digital camera on a single chip; under $10 for volume users. It is the first commercially available image sensor to have a built-in A/D converter. The Digital Video Camera Chip, VVL1070 delivers a digitized B&W image through processor-compatible serial and parallel ports. The IC uses a proprietary CMOS sensor technology developed by VLSI Vision Ltd., which also is developing a whole series of single-chip EIA cameras that will be shortly introduced to the American market.**

- **The chip features a 160 x 160 pixel array. Pixel size is 10.5 x 10.5 microns. All circuitry to drive and sense the array is packaged in a single Optical Quad Flatpak. The digital converter provides an 8-bit digital output for serial or parallel interface. Other features include an analog output with sync pulses, wide-range electronic exposure control for use with a variety of low-cost fixed-aperture lenses, and automatic black level circuitry. Power consumption is *less than 100 mw*. It is commercially available from Marshall Electronics, Culver city.**

CCD-based color camera:

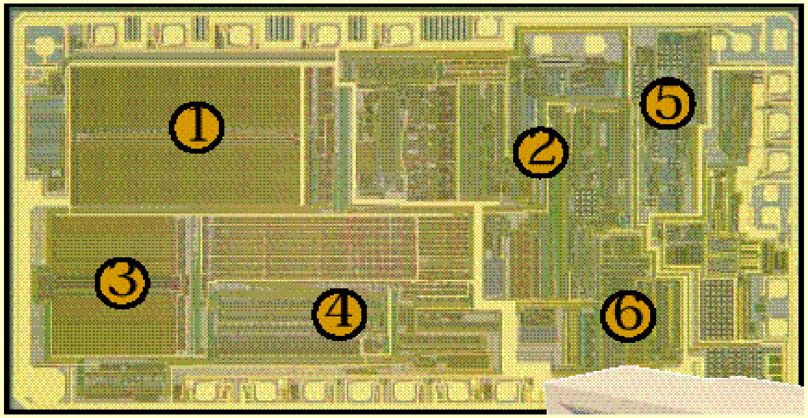
- **The Toshiba IK-M40A high resolution microminiature color camera head is 39 mm long, 17 mm diameter, and weighs 16 g. It has a 1/2" CCD with 410,000 pixels, high sensitivity (5 lux at F1.6), and an electronic shutter. Several lenses are available and the cost is about $2 k.**

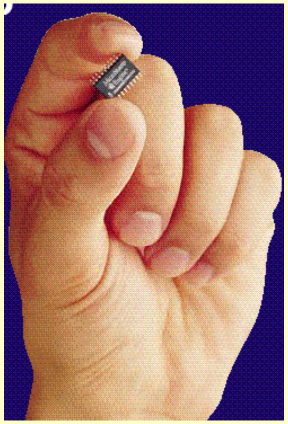
Ref: http://www.technology-in-education.co.uk/articles/AnchorSupplies/article.htm

MICROEXPLORERS: FUNCTIONAL MODULES
ON-BOARD DATA PROCESSING / COMMUNICATION

- **Low-power, limited range, low-bandwidth communication, adequate for the explorers, has been addressed rather aggressively in recent years. It targets the mass market for product ID tags and inventory control. The following is an example of a single-chip solution from Micron Corporation.**

1. **SRAM partitionable memory**
2. **Signal Pre-processing, transmit control**
3. **ROM 4 Kbytes**
4. **8-Bit microprocessor**
5. **High-frequency radio with a range ~ 15 meters**
6. **Wake-up and bias circuitry**





Micron Communications' MicroStamp™ remote intelligent communications (RIC) integrated circuit is the world's first wireless communications technology to integrate a microwave radio, a microcontroller, and memory into a single silicon chip (15.64 square millimeters).

This chip is a good example of technology readiness in the commercial marketplace. An estimate of a square cm silicon area for a microexplorer communication function is therefore quite reasonable.

Ref: http://www.micron.com

MICROEXPLORERS: FUNCTIONAL MODULES
ADVANCED MOBILTY

- **Current wheeled mobility mechanisms are generally designed for, and therefore limited to, only pre-selected terrain conditions. Even with complex suspension mechanisms, wheels can typically negotiate obstacles which are no more than about twice the wheel diameter. Furthermore, complex drive/transmission mechanisms make them more vulnerable. On the other hand, biologically inspired alternative mobility mechanisms may not only be more adaptable to various terrain conditions, they may also be more suitable for scalable manufacturing techniques. In fact, alternate mechanisms based on flexible actuators look increasingly attractive as the size of the mobile system is reduced. Flexible actuator-based active mobile appendages would be direct driven, higher efficiency, and have substantially less mechanical vulnerability. Moreover, flexible actuators could be fabricated using VLSI compatible techniques that make them batch processable and scalable from tens of centimeters down to submicron dimensions.**

- **The following chart presents a comparison of several leading smart material systems that lend themselves for fabricating innovative “actuator” building blocks for providing flexible and potentially reconfigurable custom-mobility to the microexplorers.**

ADVANCED MOBILITY
ACTUATION TECHNOLOGIES COMPARISON

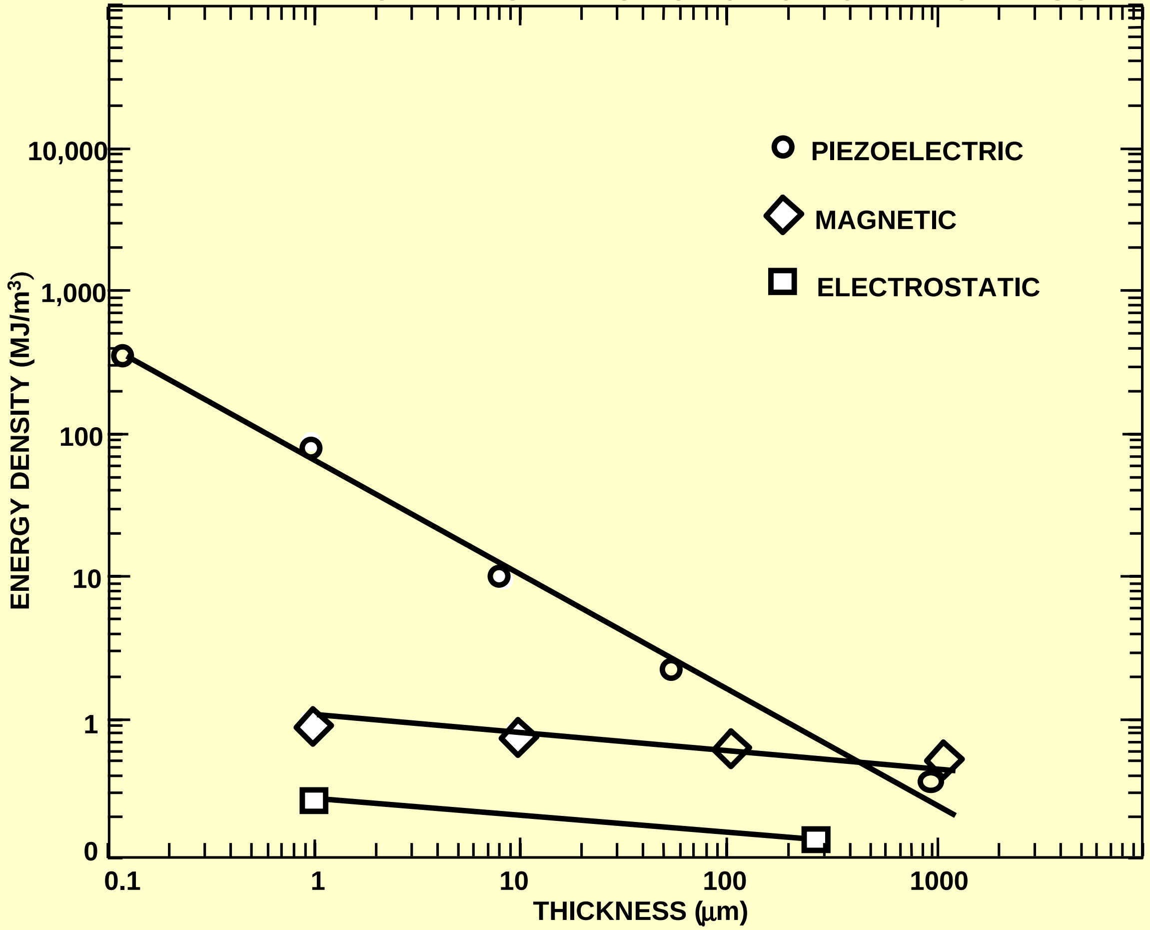
			POLYMERIC MATERIALS		
	PIEZOCERAMIC	SHAPE MEMORY ALLOY	PVDF and PVDF copolymers	Polymides PMMA Polyurethanes	MAGNETO-STRICTIVE
MECHANISM	PIEZOELECTRIC & ELECTROSTRICTIVE	THERMAL: MARTENSITIC → AUSTENITIC PHASE CHANGE	PIEZOELECTRIC, PHASE TRANSITION	ELECTRO-STRICTIVE	MAGNETIC FIELD INDUCED BY COIL
STRAIN	10^{-4} TO $0.3\text{X}10^{-2}$	10^{-5} TO 10^{-1}	10^{-6} TO 10^{-1}	10^{-9} TO 10^{-1}	10^{-5} TO 10^{-2}
DISPLACEMENT	LOW TO HIGH	MEDIUM TO HIGH	LOW TO HIGH	LOW TO MEDIUM	MEDIUM
FORCE (in Newtons)	HIGH ~ 100-1000	MEDIUM ~ 1-10	SMALL	SMALL	HIGH
HYSTERISIS	TAILORABLE BY COMPOSITION	SMALL	LARGE	SMALL TO MEDIUM	LARGE
AGING	COMPOSITION DEPENDENT	VERY SMALL	LARGE	LARGE	SMALL
TEMPERATURE RANGE OF OPERATION	–196°C → 300°C WIDE	–196°C → 100°C WIDE	–50°C → 150°C MEDIUM	–10°C → 80°C LIMITED	-273°C → 100°C WIDE
RESPONSE SPEED	µsec-msec	seconds	µsec-msec	µsec-msec	µsec-msec
ACTIVATION MODE	BOTH OPTICAL AND ELECTRICAL	THERMAL AND ELECTRICAL	ELECTRICAL	ELECTRICAL	MAGNETIC
POWER REQUIREMENT	LOW	LOW to MEDIUM	MEDIUM	LOW TO MEDIUM	HIGH
RADIATION HARDNESS	YES	YES	TBD	TBD	YES
CYCLABILITY	EXCELLENT	GOOD	FAIR	FAIR–POOR	GOOD
PROSPECT OF MINIATURIZATION	GOOD	GOOD	GOOD	GOOD	FAIR

THE SURVEY SUGGESTS LEADING CANDIDATES AND THEIR HIGHLIGHTED ATTRIBUTES

Innovative combinations of flexible actuators are conceptualized to form building blocks of the bio-morphic explorers

COMPARISON OF ACTUATION TECHNOLOGIES

ENERGY DENSITY AS FUNCTION OF THICKNESS

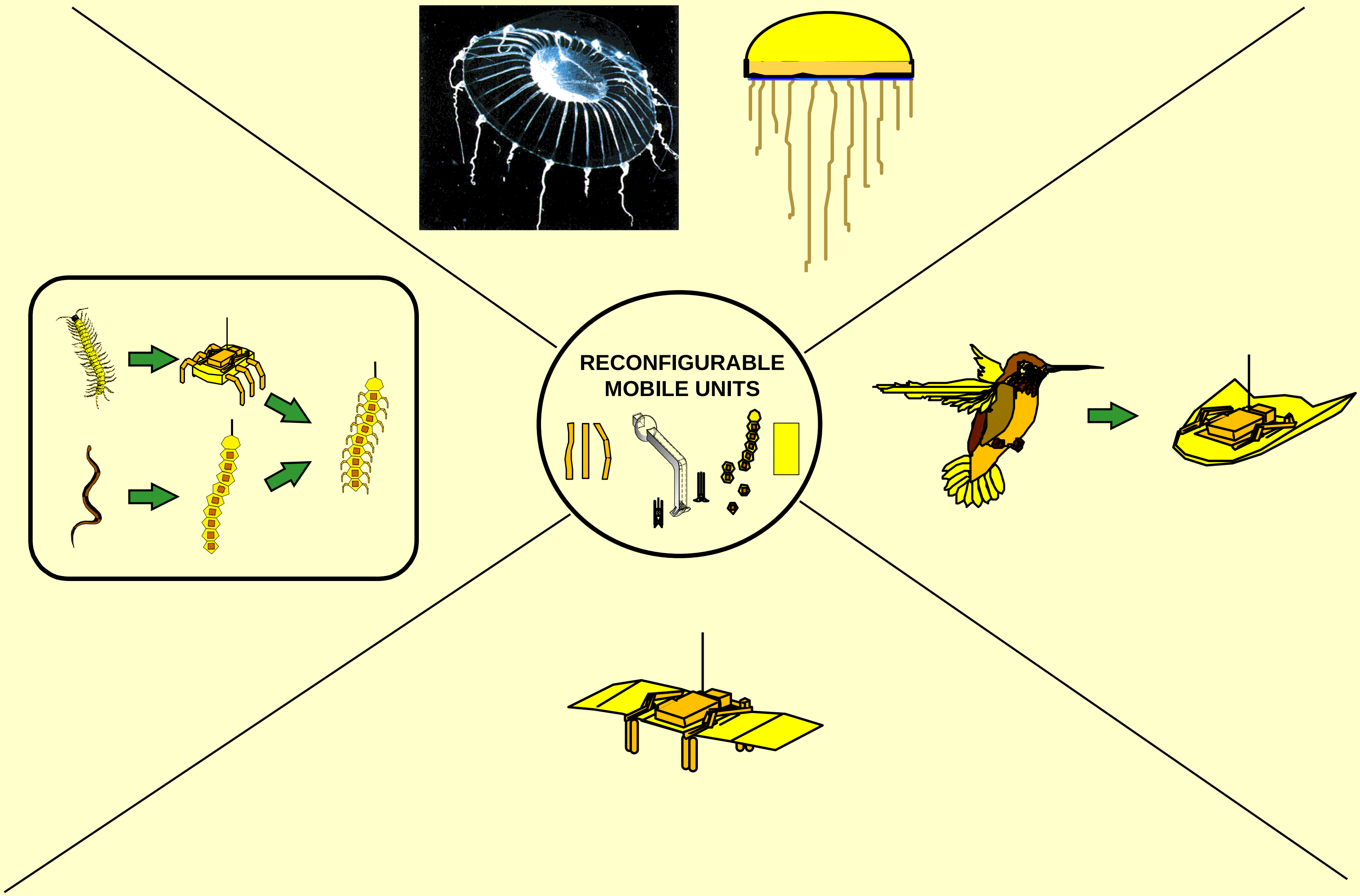


With reduction in thickness, the energy absorbed by piezoceramic actuators could be up to two orders of magnitude higher compared to electrostatic and magnetic actuators. Therefore, the same level of actuation could be achieved using components with reduced mass/volume.

FLEXIBLE ACTUATORS: INNOVATION OPTIONS

MATERIAL INNOVATION	FABRICATION CHALLENGE	PAY-OFF	FEATURES ENHANCED
I Shape memory alloy wire, Piezoceramics	LOW	MEDIUM	HIGH FORCE, MEDIUM DEFLECTION WIDE TEMP RANGE OPERATION MEDIUM SPEED, ELECTRICALLY OPERATED
II Piezoceramics thin film/high temp. polymers	MEDIUM	MEDIUM	MEDIUM FORCE, HIGH DEFLECTION SCALEABLE, MEMS WIDE TEMP RANGE OPERATION MEDIUM SPEED, ELECTRICALLY OPERATED
III Optical Piezoceramics / high temp. polymers, polymeric actuators	HIGH	HIGH	HIGH FORCE& DEFLECTION COMBINATION, SCALEABLE, MEMS WIDE TEMP RANGE OPERATION HIGH SPEED, ELECTRICALLY & OPTICALLY OPERABLE

ADVANCED MOBILITY FOR BIO-MORPHIC EXPLORERS



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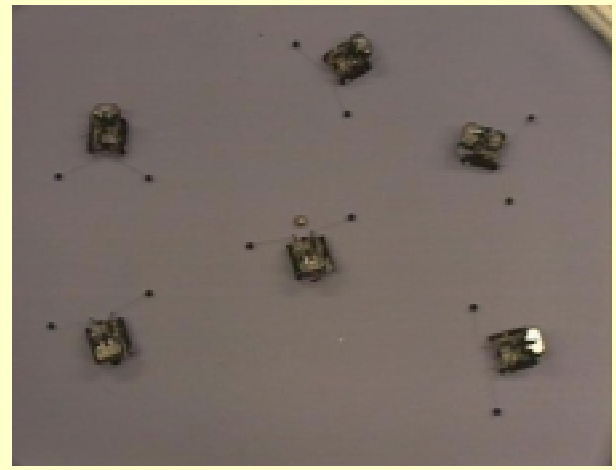
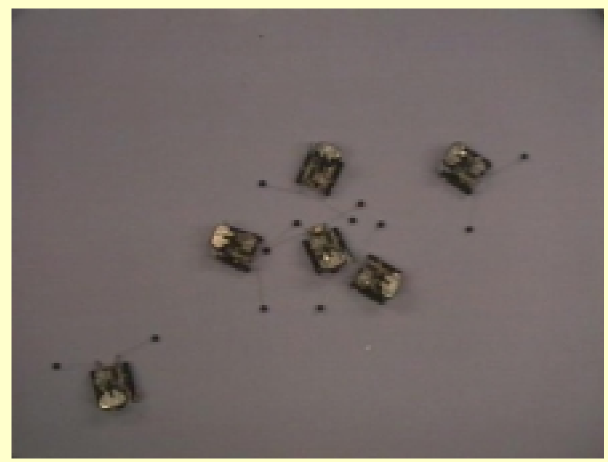
MICROEXPLORERS
COOPERATIVE BEHAVIOR

An MIT study
Social Behavior: Clustering around food





Here are two shots of the first cooperative program in action. The first picture shows the robots scattered around the playing area. There is a piece of ant food in front of the robot in the middle.

Once the robot in the middle detects the food, it emits the "I found food" IR signal. Any robot within about 12 inches can detect the signal and head in that direction.

When a robot receives the "I found food" signal it heads towards the robot with the food while transmiting "I see an Ant with food". Any robot within range of the second robot receives the "I see an Ant with food" signal, heads towards the second robot, and transmits "I see an Ant that sees an Ant with food". Any robot within range of the third robot receives the "I see an Ant that sees an Ant with food" signal and... well you get the picture. It is like a robotic relay team.

This type of behavior would be useful for efficiently collecting large ‘food’ sources on foraging trips. Although this behavior is very simple, when it is combined with other behaviors and there are many robots interacting with each other, you can get some very interesting results.

Ref: http://www.ai.mit.edu/projects/ants/social.behaviour..html

MICROEXPLORERS
COOPERATIVE BEHAVIOR

- **Information (short signals) "relayed" by explorers to each other and/or to the lander/mothership is clearly a simple and inexpensive method of cooperation. While searching for the goal, perhaps the only signal that would go out would be a periodic "I am alive" beep. When the goal (say a chemical, water, etc) is found, the signal may change to "eureka". Whether the position/coordinates also need to be transmitted to the mothership would depend on the overall area covered and the spatial resolution required. Clearly, for a sample collecting explorer, the knowledge of relative position would be critical to be able to find the "home" base for unloading the "catch".**

References:

1. Cao Y, Fukunaga AS, Kahng AB; "Cooperative Mobile Robotics: Antecedents and Directions", Autonomous Robots **4,** pp 7-27, 1997.
2. Maes P, Brooks R; "Learning to Coordinate Behaviors." In Proceedings of the Eighth National Conference on Artificial Intelligence, pp.796-802, 1990.
3. Mataric M.; " Interaction and Intelligent Behavior", Ph.D. Dissertation, MIT EECS Dept., 1994.
4. Parker L.; "Heterogenous Multi-Robot Cooperation", Ph.D. Dissertation, MIT EECS Dept., 1994.

RECOMMENDATIONS FOR FUTURE WORK

- **A future trade study should include consideration of various exploration architectures with respect to their science value and cost, and, in the process, there should be due consideration of storage and deployment mechanisms of the microexplorers. Three candidate architectures that could be considered are:**

  - **Cooperative behavior among many biomorphic explorers could enable new types of missions. Using groups of small, inexpensive biomorphic explorers in conjunction with larger, traditional mobile robots could enable tasks which are too complex for a single robot. Also, it could allow a wide range of sample collection.**

  - **Exploration for life may include a lander/rover (mothership) and multiple small explorers working in concert. Multiple here means not just a few but potentially 100's or 1000's of the explorers peppering the exploration site for an exhaustive survey. Constructed of foldable building blocks occupying low mass and volume, a large number of explorers could be stacked/stored on a long-range mother rover. For instance, in exploring ejecta from a crater, the mother rover could focus on traversing large distances (say ~ 10 KM, to cover the entire crater) and the biomorphic explorers could be spread out to do localized sample survey/acquisition.**

  - **Autonomous biomorphic explorers with advanced mobility, memory and computational capabilities could track their path back to the lander/rover (mothership). If they make a "eureka" discovery, they could communicate the data by returning and attaching to the mothership, thereby by-passing the need for telecom.**

RECOMMENDATIONS FOR FUTURE WORK (contd)

- **Perform detailed subsystem and system engineering analyses with the aid of 'CAD' tools and generate strawman designs with multiple options. Quantify the science information that can be returned within each volume allocation.**
  - **Incorporating the real physical parameter values for selected components in simulations will help validate/narrow-down the choices.**
  - **Simulations will also help stimulate interest in building selected biomorphic explorer prototype hardware.**
- **Prioritize technology needs and develop a realistic technology development roadmap to implement microexplorers.**
- **Identify synergistic potential applications of biomorphic explorers in the defense, commercial and academic sectors to pave the way for cooperative R & D dollar leveraging.**
- **Establish a focussed biomorphic explorers working group**
- **Develop a new paradigm for exploration utilizing microexplorers. Identify/select a NASA-relevant planetary exploration application scenario and demonstrate a microexplorer prototype utilizing the selected architecture and detailed optimized design.**

TECHNOLOGY DEVELOPMENT RECOMMENDATIONS

- **Advanced mobility with unconventional materials and control algorithms needs focussed research & development investment to exploit/realize the promise of microexplorers**

  - **Develop innovative biomechatronic designs based on reconfigurable mobile units and biomorphic controls. Burrowing down is of interest for Mars subsurface exploration. Fluid navigation mechanisms are of pertinence for Europa subsurface ocean exploration. Mechanisms providing enhanced spatial access and foldability are crucial for sample collection from hard-to-reach locations.**

  - **Evaluate the advanced control algorithms and co-operative algorithms/architectures in realistic terrain conditions.**

- **An important aspect in selecting/optimizing materials and designing microexplorers would be the desired temperature of operation for the microexplorers:**

  - **Planets are often frigid, and temperatures encountered could be quite extreme. Performance characterization of the on-board electronics and any new materials used for mobility (e.g., PZT/PLZT, SMA, etc) for such conditions is crucial These advanced materials need to be qualified for low temperature operation.**

  - **If low temperature conditions are known to be predominant in a specific mission, the electronics will have to be designed for low temperature operation or a heating circuit (and corresponding power) providing a constant thermal temperature will have to be accommodated.**

- **Customization of the selected sensors from the rapidly advancing field of micro-sensors (size, shape, configuration, packaging, electronics, power requirements, cyclability, durability, etc) would be required to integrate them on specific microexplorer structures.**

CONCLUSIONS

- Realization of the vision of microexplorers requires at least four key components: microsensors, micropower, advanced mobility, and microcommunication devices. Of these, all except advanced mobility are already driven by multibillion dollar commercial market forces. Advanced mobility deserves a focused effort.

- Particularly for the smallest microexplorers, availability of extremely small, robust, high-energy-density primary and/or secondary batteries is essential for microexplorer viability. Environmental compatibility (particularly with regard to storage and operating temperature ranges), voltages, and charge/discharge characteristics are also important considerations.

- Methods need to be developed for both navigating through desired search patterns and navigating to desired areas, as well as knowing coordinates of locations where measurements are made. This may be difficult because it will probably not be easy to accurately measure distance and direction traveled, and there will be few resources available for adding navigation sensors.

- Even with the availability of small components, sensor integration and compact overall packaging are likely to be challenging. Also, while the theoretical mass percentage of needed integrating structure may be quite low in this size regime, it may be difficult to realize masses as low as this due to integration complexities and minimum thicknesses of readily available material.

- Since it is necessary for the recurring costs of microexplorers to be quite low, it is important to design them for ease of assembly and test, and to use modularity and standardization of interfaces (at least within a microexplorer family).

- Once microexplorers have been developed and their use is common, a further step in microexplorer sophistication may be warranted in which the capability of partial functional reconfiguration is added to the larger microexplorers. This could enable them to operate better in changing environments and to return more valuable information.

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